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Iterative time reversal simulation for selective focusing in multi-target nonlinear media

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Abstract

In High Intensity Focused Ultrasound (HIFU), when multiple targets are present in a linear medium, ultrasound can focus on the strongest target by using an iterative time-reversal(TR) method. However, the validation of iterative TR in nonlinear human tissue still needs to be investigated. In the study, the TR and iterative TR processes are numerically simulated with a finite difference method in two dimension, considering the nonlinear effects. Results show that TR is valid in nonlinear human tissues with some difference in focus accuracy and intensity gain comparing to that in linear media. The nonlinearity of the media increases the intensity gain at the focal point, while the absorption decreases the focal gain and changes the position of the focal spot. Iterative TR works well in nonlinear media and the lobe on the weaker target attenuates more rapidly than in linear media.

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Keywords: time reversal, nonlinear media, numerical simulation, beam focusing, HIFU

1. Introduction

High intensity focused ultrasound (HIFU) is a promising non-invasive medical technology. It uses high-intensity focused ultrasound to heat and destroy pathogenic tissue rapidly through ablation[1]. Time reversal(TR) introduced by Fink et al.[2] is a good way to focus precisely when the required focal point is a reflective target. Prada et al.[3, 4] proposed an iterative mode of TR to automatically focus on the brightest reflective target and studied its efficiency theoretically and experimentally. Peng et al.[5] implemented numerical simulations of iterative TR in layered media and discussed its accuracy and efficiency.

Theoretically, TR is based on linear and lossless sound field. But the high intensity ultrasound impinging on body tissues brings about nonlinearity and thermoviscous absorption that might change the accuracy and intensity gain of the focus. Cunningham et al.[6] studied the effect of nonlinearity on the application of TR and Liu et al.[7] conducted numerical simulations using KZK equation. The nonlinearity impact on TR and iterative TR focus in human body under HIFU circumstances still needs to be investigated. In this paper, we use numerical simulations of iterative TR based on the Westervelt equation considering nonlinearities and absorption of human body tissues in HIFU to study the effect on TR and iterative TR in nonlinear sound field.

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2. Method

The acoustic wave field in an inhomogeneous thermoviscous medium can be described by a modified Westervelt equation introduced by Hamilton and Morfey[8]:

$$\nabla^2 p - \frac{1}{\rho_0}\nabla\rho \cdot \nabla p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{\delta}{c_0^4}\frac{\partial^3 p}{\partial t^3} + \frac{\beta}{\rho_0 c_0^4}\frac{\partial^2 p^2}{\partial t^2} = 0 \tag{1}$$

where p is the sound pressure, c_0 is the small signal sound speed, δ is the sound diffusivity for a thermoviscous fluid, β is the nonlinearity coefficient and ρ_0 is the ambient density. c and ρ are the sound speed and the density of the medium respectively that can vary in space. The sound diffusivity is given by $\delta = \frac{2c_0^3\alpha}{\omega^2}$, where α is the absorption coefficient, ω is the angular frequency.

The process of TR can be described as the following three main steps: (1)An element in the center of the ultrasonic transducer array is excited by a broadband signal, and an ultrasound wave propagates through the medium that contains one or more reflective targets. (2)The waves reflected by the targets are received by all the elements of the transducer array. (3)The received signals are editted to neglect the direct waves, time reversed, and reemitted by all the elements simultaneously. The first transmitted wave is small in amplitude and the wavefield is linear, while in the following steps the nonlinear effects need to be considered. These steps can iterate in order to selectively focus the ultrasound onto the target with the strongest reflectivity.

To numerically simulate the TR and iterative TR process, we use the models shown in Fig. 1. A 32-element linear array with an aperture of 160mm and a central frequency 500Hz is used to focus the ultrasound in a homogeneous medium. In the first model, one reflective target of radius 1mm is placed on the axis of the transducer array, with a depth of 150mm. In the second model, two reflective targets of radius 1mm with different impedences are placed 10mm off the axis with the same depth of 150mm. The background medium has a density 1000kg/m^3 and a sound velocity 1540m/s. The targets in Fig. 1(a) and on the right of Fig. 1(b) has a reflectivity 2, while the left target in Fig. 1(b) has a reflectivity 1.5. The absorption and nonlinearity coefficients are in the range $0 < \alpha < 10$Np/m and $0 < \beta < 20$, which are chosen in accordance with real human tissue characteristics. A finite difference method in two dimension is used to solve the wave equation and obtain the sound field.

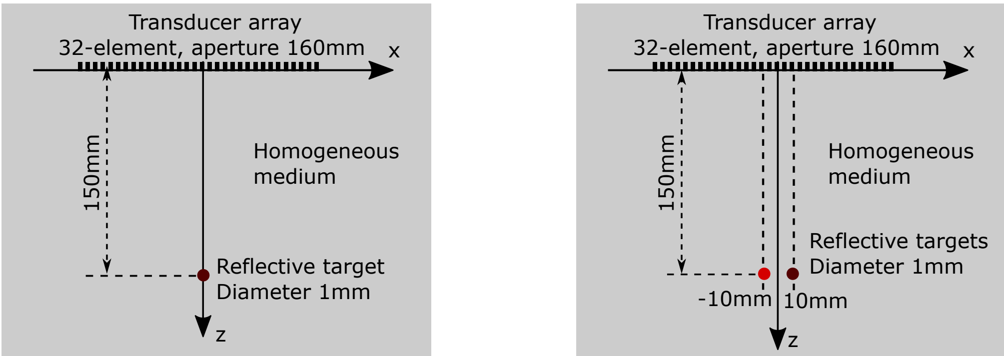

Fig. 1. (a) TR simulation model with one reflective target embedded in a homogeneous medium; (b) Iterative TR simulation model with two different reflective targets in a homogeneous medium.

3. Results

3.1. TR with single target

For the model with one single target, we numerically simulate the TR process with nonlinearity and absorption coefficients $\beta = 0$, $\alpha = 0, 5, 10$Np/m and $\alpha = 0$Np/m, $\beta = 0, 10, 20$. The resulting amplitude patterns of sound pressure in the plane of the target are shown in Fig. 2. The amplitudes are normalized to the linear case when

α = 0Np/m and β = 0. Fig. 2(a) shows the pressure distribution change due to absorption coefficient varying in the range of 0 – 10Np/m. Clearly, the intensity gain at the focal point significantly decreases when absorption coefficient increases. In Fig. 2(b) where absorption is set to zero and only nonlinearity coefficient is considered, the focal gain of intensity increases with the nonlinearity coefficient β within the range of 0 – 20.

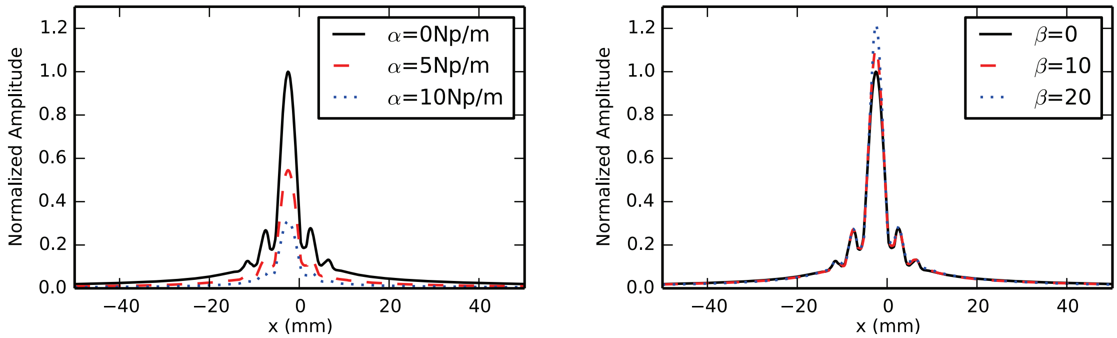

Fig. 2. (a)Impact of absorption to amplitude distribution in the focus plane;(b)Impact of nonlinearity to amplitude distribution in the focus plane.

The accuracy of the focus is another important issue in HIFU. We evaluate the focal depth, focal spot width and length changes due to absorption and nonlinearity variations within the range of $0 \leq \alpha \leq 10$Np/m and $0 \leq \beta \leq 20$, as shown in Fig. 3. The focal point is picked at the peak of the pressure amplitude field. The focal spot width is picked in the focus plane where the pressure amplitude reduces to -3dB from the peak value, while the focal spot length is picked in the same way along the transducer axis. From Fig. 3(a) it can be found that nonlinearity does not affect the position of focus, while absorption effect makes the focal point closer to the transducer. Fig. 3(b) and (c) show that absorption makes the focal spot bigger, while nonlinearity makes the focal more concentrated.

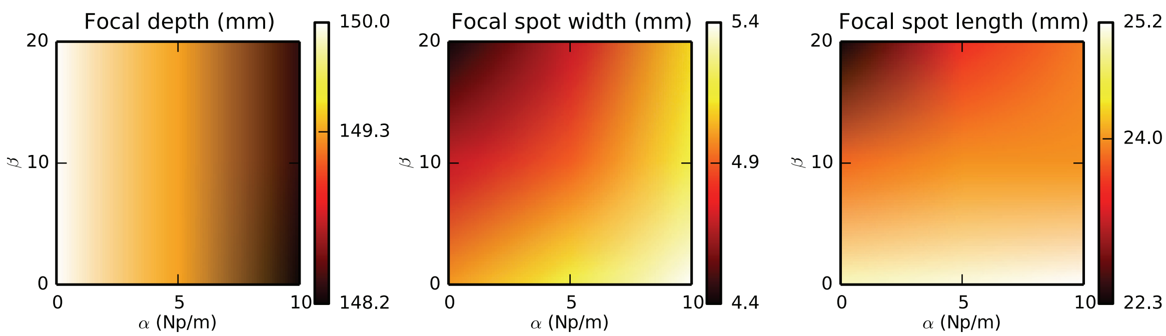

Fig. 3. Focal spot position and size changing with absorption coefficient α and nonlinearity coefficient β: (a)focal depth (mm);(b)focal spot width (mm);(c)focal spot length (mm).

3.2. Iterative TR with multiple targets

For the model with two reflective targets with different reflectivities, we conduct iterative TR process numerically with absorption coefficient α = 10Np/m and nonlinearity coefficient β = 20. The resulting pressure amplitude patterns in the target plane are compared in Fig. 4(a). At the first TR operation, the pressure amplitude diagram shows two lobes at the positions of the tagets, one stronger than the other. With each iteration, the pressure at the lower peak decreases rapidly. We compare the amplitude of the weaker lobe after each iteration while normalizing the amplitude of the main lobe in Fig. 4(b). The result of a corresponding linear model is shown in dot line as a reference. It is shown that the weaker lobe attenuates more rapidly when nonlinearity exists.

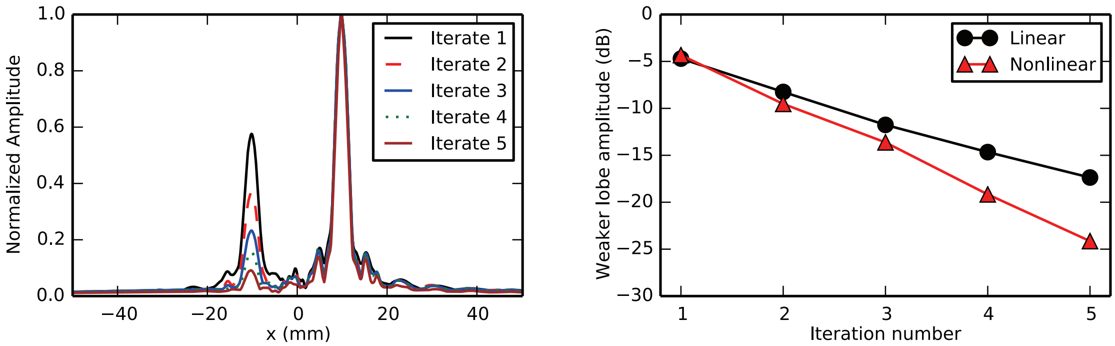

Fig. 4. (a) Amplitude distribution in target plane after each TR iteration for the nonlinear model with two targets.(b) Attenuation curve of the weaker lobe.

4. Conclusion

Numerical simultions of TR and iterative TR based on the Westervelt equation is used to investigate the validation of TR and iterative TR in HIFU in nonlinear media. The absorption coefficient α decreases the focal gain and makes the focal point nearer to the transducer. The nonlinearity coefficient β of human tissue does not change the position of the focal spot, but makes the focus sharper. Iterative TR is valid in nonlinear human tissues and the lobe on the weaker target attenuates even more rapidly than in linear media.

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